JNCC Report
No. 665c

Nitrogen Futures
Annex 3: Selecting metrics

Ed Rowe, Tony Dore, Laurence Jones, Chris Field, Simon J.M. Caporn, Carly Stevens, Ed Carnell & Ulli Dragosits

October 2020

ISSN 0963-8091

For further information please contact:

Joint Nature Conservation Committee
Monkstone House
City Road
Peterborough PE1 1JY
www.jncc.gov.uk

This report should be cited as:

Rowe, E., Dore, T., Jones, L., Field, C., Caporn, S.J.M., Stevens, C., Carnell, E. & Dragosits, U. 2020. Nitrogen Futures - Annex 3: Selecting metrics. JNCC Report No. 665c. JNCC, Peterborough, ISSN 0963-8091.

JNCC EQA Statement:

This report is compliant with the JNCC Evidence Quality Assurance Policy available at: https://jncc.gov.uk/about-jncc/corporate-information/evidence-quality-assurance/

JNCC would like to thank Alastair Burn, Clare Whitfield, Tom Pearson, David Vowles, Susan Zappala and Alexandra Cunha for their valuable review of this report.

Summary

Metrics can be useful for communicating and assessing the benefits to ecosystems of decreases in nitrogen (N) pollution. The “Nitrogen Futures” project developed a set of criteria for assessing different metrics and used these criteria to select metrics to use in the main report for illustrating results of different pollution scenarios.

In this annex we describe how metric evaluation criteria were developed, and discuss metrics of:

1. Emissions
2. Exposure
3. Designated sites
4. Effects on vegetation
5. Effects on ecosystem condition

Emissions metrics represent overall pressure on ecosystems, and metrics of exposure the pressure on particular sites and/or habitats. “Designated site metrics” are indicators developed to assess the risk from nitrogen pollution to sites designated for their nature conservation interest. Vegetation effects metrics are calculated in relation to critical loads or critical levels, i.e. pollution fluxes or concentrations, respectively, which are considered to be potentially harmful. Ecosystem condition metrics are measurements or summaries of either plant community composition or biogeochemical properties of the system such as nitrogen content. All potentially useful metrics are summarised, and evaluation scores are presented. The metrics are ranked, and selected metrics are proposed for use in scenario assessments.

Contents

Glossary

Acronym	Meaning
AAE	Annual Average Exceedance
ASSI	Area of Special Scientific Interest (Northern Ireland), equivalent of SSSI in Great Britain
AENEID	Atmospheric Emissions for National Environmental Impacts Determination. A model to produce high-resolution (1 km grid) maps of agricultural ammonia, methane and nitrous oxide emissions for the UK, annual maps available through the NAEI
BAU	Business As Usual - includes only those policies that have already been adopted or implemented at the time of the project projection compilation. It does not include additional measures set out in the NAPCP which are designed to meet NECD/NECR targets.
CBED	Concentration-Based Estimated Deposition, a model generating maps of deposition of sulphur, oxidised and reduced nitrogen
CCE	Coordination Centre for Effects, of the WGE
CNCBs	Country Nature Conservation Bodies (Natural England, Scottish Natural Heritage, Natural Resources Wales, Council for Nature Conservation and the Countryside)
CL	Critical Load, an amount of deposition per unit area and time. The formal definition is "a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge" (Nilsson & Grennfelt 1988)
CLe	Critical Level, a concentration in air e.g. of ammonia, below which harmful effects do not occur according to present knowledge
CL_{empN}	Empirical critical load for nutrient-nitrogen, as defined in Bobbink *et al*. (2011) and refined for the UK by Hall *et al*. (2011)
CLRTAP	Convention on Long Range Transboundary Air Pollution
DA	Devolved Administration
Daera	Department of Agriculture, Environment and Rural Affairs
Defra	Department for Environment, Food & Rural Affairs
ECA	Emission Control Area
EDZ	Emission Displacement Zone
ELM	Environmental Land Management
ERC	Emission Reduction Commitments
ERZ	Emission Reduction Zone
EU	European Union
FAPRI	Food and Agricultural Policy Research Institute
FRAME	Fine Resolution Atmospheric Multi-pollutant Exchange (atmospheric chemistry and transport model)
ha	Hectares. One hectare is 100 m x 100 m
ICP-M&M	International Cooperative Programme for Modelling and Mapping critical loads and critical levels.
IED	Industrial Emissions Directive
LEZ	Low Emission Zone (a defined area where access by some polluting vehicles is restricted with the aim of improving air quality)
MCPD	Medium Combustion Plant Directive
N	Nitrogen. Strictly, reactive N, i.e. including oxidised and reduced forms of N but not dinitrogen gas, N_2.
NAEI	UK National Atmospheric Emissions Inventory
NAMN	UK National Ammonia Monitoring Network
NARSES	UK agricultural emission model (spreadsheet based), developed by Rothamsted Research
NAPCP	National Air Pollution Control Programme
NE	Natural England
NECD	EU Directive on the Reduction of National Emissions (2016/2284)
NECR	UK National Emission Ceilings Regulations (2018 No 129) transposing NEC Directive 2016/2284/EU.
NFC	UK National Focal Centre, under ICP-M&M

NFR	Nomenclature for Reporting (Format for reporting of national emission data in accordance with the CLRTAP)
NH_3	Ammonia
NMVOC/VOC	Non-Methane Volatile Organic Compounds/Volatile Organic Compounds
NO_x	Nitrogen Oxides
NRMM	Non-Road Mobile Machinery
NRW	Natural Resources Wales
MCPD	Medium Combustion Plant Directive
PaMs	Policies and Measures
PCM	Pollution Climate Mapping (model)
PM	Particulate Matter
SAC	Special Area of Conservation, designated site protected under the Habitats Directive
SEPA	Scottish Environment Protection Agency
SNAP	Shared Nitrogen Action Plan
SNAP (sectors)	Selected Nomenclature for reporting of Air Pollutants. Pollution sources categorised into sectors for reporting. For example: S3 – Combustion in manufacturing industry, S7 – Road Transport, or S10 Agriculture.
SNCBs	Statutory Nature Conservation Bodies (Joint Nature Conservation Committee, Natural England, Scottish Natural Heritage, Natural Resources Wales, Northern Ireland Natural Environment Division)
SNH	Scottish Natural Heritage
SO_2	Sulphur Dioxide
SPA	Special Protection Area
SSSI	Site of Special Scientific Interest
UAN	Urea Ammonium Nitrate (a liquid fertiliser combining urea, nitric acid, and ammonium)
WAM	With Additional Measures. This scenario includes policies that have been adopted and implemented as well as those that are planned.
WGE	Working Group on Effects, within CLRTAP
WM	With Measures. This scenario includes policies that have been adopted and potentially implemented at the time of projection compilation.
WP	Work Package

1 Introduction to nitrogen pollution metrics

1.1 Background

Metrics can be useful for communicating and assessing the benefits to ecosystems of decreases in nitrogen (N) pollution. The "Nitrogen Futures" project used a selection of metrics to illustrate results of different pollution scenarios.

In this annex we describe some proposed metrics and assess which are suitable for this scenario analysis and which are potentially useful but not applicable in the current study. An initial long list of metrics was circulated in August 2019, and feedback received. Criteria for evaluating and shortlisting metrics, and methods for applying these criteria, were agreed in early September 2019. The proposed metrics were evaluated according to these criteria and shortlisted. This document describes a short list of recommended metrics. Stakeholders with an interest in the project outcomes were asked in November 2019 to assess the criteria, and the scores assigned. The evaluations of metrics that we present below take these responses into account.

1.2 Selecting metrics to include

Numerous metrics of different types were suggested and discussed during the initial phase of the project. On reflection, some of these metrics were considered unsuitable to take forward because they did not meet certain essential criteria, i.e.:

- With a specific and concrete definition;
- Scientifically robust and with an acceptable level of uncertainty (e.g. peer-reviewed), or with the potential to be so in the near future;
- Enable the assessment of benefits for protected sites and/or sensitive habitats in the wider countryside through the lens of legislative obligations and policy objectives for the environment; and
- Sufficiently sensitive to express meaningful change over the study period, i.e. baseline (2017) to 2030 and towards 2040 and beyond).

Metrics considered unsuitable are listed in the Conclusions section (Table 6). Metrics that met all of these essential criteria were shortlisted and are described briefly in the 'Potential Metrics' section. These metrics are those considered most useful for:

a) Application (at least potentially) within the current 'Nitrogen Futures' project for scenario explorations (listed in Table 4), and/or
b) Application beyond the current project, for example for site condition assessment (listed in Table 5).

Each shortlisted metric is described in simple terms. A proposed method for measuring and/or calculating each metric is presented, to avoid ambiguities. These metrics were evaluated against further "desirable" criteria (Table 1), each of which was given an importance weighting. Each metric was given a score (0-2) for the degree with which it meets each of these desirable criteria – these scores are shown in this annex. An overall score for each metric was calculated as the sum of (score x importance) for all the desirable criteria.

Table 1. Desirable criteria against which metrics were assessed, and weightings used to calculate a score for the metric.

Criterion	**Short name**	**Importance 1 (low) to 3 (high)**
Communicates benefits in a manner easily visualised and understood by non-experts.	Clear	3
Based on open or readily accessible data.	Open	2
Help fulfil existing UK/country specific targets or objectives or inform the setting of these in future strategies, e.g. “reduction of damaging deposition of reactive forms of nitrogen by 17% over England’s protected priority sensitive habitats by 2030”* outlined in the UK Government’s Clean Air Strategy.	Targets	3
Applicable in the current project, for calculation of effects of different emissions scenarios.	Scenarios	1
Sufficiently sensitive to show gradual improvements rather than purely binary (i.e. above/below critical load or critical level).	Sensitive	3
Suitable for assessing impacts and benefits at a range of scales from individual sites to regional (e.g. a county, or a large site), DA and UK scale. As part of the assessment, the scale aspect will be discussed (e.g. some metrics may work better at smaller or larger scales).	Scales	3
Easy to use/application e.g. by a site manager, requiring little effort.	Easy	3
Compatible with or complementary to currently applied UK methodologies and international best practice.	International	2
Suitable for assessing impacts on charismatic groups, e.g. butterflies, pollinators, orchids, reptiles or birds.	Charismatic	3
Suitable for assessing impacts on designated features on protected sites.	Sites	2
Endpoint indicator i.e. directly reflects impacts that people are concerned about or reflects an important ecological impact.	Endpoint	3
Resilience indicator or enables linkage of air quality effects on ecosystems to cross-cutting or global issues such as climate change/carbon storage.	Cross-cutting	2

* The calculation of this metric is discussed in more detail in section 2.2.1 below.

We discuss metrics of:

1. Emissions
2. Exposure
3. Designated sites
4. Effects on vegetation
5. Effects on ecosystem condition

“Designated sites” are sites with a nature conservation designation, such as SSSIs, ASSIs, SACs and SPAs. Metrics are listed below in descending order of overall score within each category. The first metric in each category should therefore be considered the best or most-recommended metric. Metrics of ecosystem condition are measurable aspects such as species richness or leaf nitrogen content, and none was considered suitable for use in the current study. This is mainly because calculating them for the future scenarios (where a predictive model is available) would have required more time and would have introduced more uncertainty. However, it is important to consider different aspects of ecosystem benefit, and metrics from every category may be useful for assessment and communication.

Several metrics make use of the empirical critical load for nutrient nitrogen (CL_{empN}). Values of CL_{empN} have been assigned to sensitive habitats, as defined using the EUNIS classification, on the basis of a review of empirical evidence (Bobbink & Hettelingh 2011). As with other critical loads, CL_{empN} represents a quantitative estimate of exposure below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge.

A summary of the scores assigned to each metric is presented next for both metrics that were later calculated for project scenarios as described in the main report (Table 2), and for metrics that are potentially useful but for which data were not available within the current project (Table 3). The metrics are discussed in more detail below.

1.3 Summary of scores assigned

Table 2. Summary of evaluation scores, for metrics that were calculated within the current project. The criteria are explained in more detail in Table 1. The weighting applied to each criterion is shown (0 is low and 3 is high weighting).

Metric Name	Clear (3)	Open (2)	Targets (3)	Scenarios (1)	Sensitive (3)	Scales (3)	Easy (3)	International (2)	Charismatic (3)	Sites (2)	Endpoint (3)	Cross-cutting (2)	Total	Weighted Total
Emissions metrics														
1.1 Agricultural emission density around designated sites (concentric zones) – measure of local pressure	2	1	0	2	2	2	2	2	0	1	0	0	14	34
1.2 Local spatial emission reductions (e.g. within buffer zones surrounding designated sites)	2	1	1	2	2	2	0	2	0	1	0	0	13	31
1.3 Sectoral emissions reductions (e.g. NH_3 by livestock category)	2	2	1	2	2	1	0	2	0	0	0	0	12	28
1.4 National (UK) emissions reductions (NH_3, NO_x)	2	2	1	2	2	1	0	2	0	0	0	0	12	28
1.5 Regional emissions (NH_3, NO_x) – Devolved Administration level (E, W, Sc, NI)	2	2	1	2	2	1	0	2	0	0	0	0	12	28
Metrics of exposure														
2.1 Annual deposition of total N (vegetation specific)	2	2	2	2	2	2	2	2	0	2	0	0	18	44
2.2 Atmospheric concentration of NH_3	2	2	1	2	2	2	2	2	0	2	0	0	17	41
Designated site metrics														
3.1 Nitrogen Decision Framework: National evidence (Factor 1 score)	1	2	2	2	1	2	2	2	0	2	1	1	18	43
Vegetation effects metrics														
4.1 Exceedance of critical level for ammonia: amount of exceedance	2	2	1	2	2	2	1	1	0	2	0	1	16	38
4.2 Average Exceedance or Excess Nitrogen of CL_{empN}, in kg N ha^{-1} yr^{-1}. These are proposed alternative names for Average Accumulated Exceedance, which has caused confusion as a term since it is based on averaging across an area, not cumulative deposition	1	2	1	2	2	2	1	2	0	1	0	1	15	35
4.3 Exceedance of critical load for nutrient-N: amount of exceedance	1	2	1	2	2	1	1	2	0	2	0	1	15	34
4.4 Exceedance of critical load for acidity: amount of exceedance	1	2	1	2	2	1	1	2	0	2	0	1	15	34
4.5 Area of sensitive habitat (for specific habitats, including priority habitats) where CL_{empN} is exceeded (% of total sensitive-habitat area)	2	2	1	2	2	1	1	2	0	0	0	1	14	33

Metric Name	Clear (3)	Open (2)	Targets (3)	Scenarios (1)	Sensitive (3)	Scales (3)	Easy (3)	International (2)	Charismatic (3)	Sites (2)	Endpoint (3)	Cross-cutting (2)	Total	Weighted Total
4.6 Area of protected sites (reported separately for SACs, SPAs and SSSIs/ASSIs) where CL_{empN} is exceeded for at least one sensitive feature	**1**	**2**	**1**	**2**	**2**	**1**	**1**	**0**	**0**	**2**	**0**	**1**	**13**	**30**

Table 3. Summary of evaluation scores, for metrics considered potentially useful but for which data were not available within the current project. The criteria are explained in more detail in Table 1. The weighting applied to each criterion is shown (0 is low and 3 is high weighting).

Metric Name	Clear (3)	Open (2)	Targets (3)	Scenarios (1)	Sensitive (3)	Scales (3)	Easy (3)	International (2)	Charismatic (3)	Sites (2)	Endpoint (3)	Cross-cutting (2)	Total	Weighted Total
Metrics of exposure														
2.3 Cumulative deposition of total N in preceding 5 years (vegetation specific)	**2**	**2**	**1**	**2**	**1**	**2**	**1**	**0**	**0**	**0**	**0**	**1**	**12**	**29**
2.4 Cumulative deposition of total N in preceding 30 years (vegetation specific)	**2**	**2**	**0**	**2**	**0**	**2**	**1**	**0**	**0**	**0**	**0**	**1**	**10**	**23**
2.5 Annual deposition of NH_y (vegetation specific)	**1**	**1**	**0**	**2**	**2**	**1**	**1**	**0**	**0**	**1**	**0**	**0**	**9**	**21**
2.6 Annual deposition of NO_x (vegetation specific)	**1**	**1**	**0**	**2**	**2**	**1**	**1**	**0**	**0**	**1**	**0**	**0**	**9**	**21**
2.7 Annual wet deposition of N	**1**	**1**	**0**	**2**	**2**	**1**	**1**	**0**	**0**	**1**	**0**	**0**	**9**	**21**
2.8 Annual dry deposition of N	**1**	**1**	**0**	**2**	**2**	**1**	**1**	**0**	**0**	**1**	**0**	**0**	**9**	**21**
Designated site metrics														
3.2 Nitrogen Decision Framework: Site-based evidence (Factor 2 score)	**2**	**1**	**2**	**0**	**1**	**1**	**1**	**1**	**1**	**2**	**2**	**1**	**15**	**40**
Ecosystem condition metrics														
5.1 Number of positive indicator species present, e.g. Common Standards Monitoring species	**2**	**2**	**1**	**0**	**2**	**2**	**2**	**1**	**0**	**2**	**2**	**0**	**16**	**43**
5.2 Species richness (including breakdown to vascular species and lower plants)	**2**	**1**	**1**	**0**	**2**	**2**	**1**	**1**	**0**	**2**	**2**	**2**	**16**	**42**
5.3 Grass:forb ratio (& variants thereof)	**2**	**1**	**1**	**0**	**2**	**2**	**2**	**1**	**0**	**2**	**2**	**0**	**15**	**41**
5.4 Mean habitat suitability for positive indicator species modelled using MultiMOVE	**1**	**1**	**2**	**0**	**2**	**2**	**0**	**2**	**1**	**2**	**1**	**1**	**15**	**39**
5.5 Species-based metrics of eutrophication, e.g. nitrophobe/nitrophile indices	**2**	**1**	**1**	**0**	**2**	**2**	**1**	**1**	**0**	**2**	**0**	**0**	**12**	**32**

Metric Name	**Clear (3)**	**Open (2)**	**Targets (3)**	**Scenarios (1)**	**Sensitive (3)**	**Scales (3)**	**Easy (3)**	**International (2)**	**Charismatic (3)**	**Sites (2)**	**Endpoint (3)**	**Cross-cutting (2)**	**Total**	**Weighted Total**
5.6 Mean 'Ellenberg N' (eutrophication) score for present species	**1**	**1**	**1**	**0**	**2**	**2**	**1**	**1**	**0**	**2**	**0**	**0**	**11**	**29**
5.7 Mean 'Ellenberg R' (acidity) score for present species	**1**	**1**	**1**	**0**	**2**	**2**	**1**	**1**	**0**	**2**	**0**	**0**	**11**	**29**
5.8 Cover-weighted mean typical height for present species	**2**	**1**	**1**	**0**	**2**	**0**	**1**	**1**	**1**	**2**	**0**	**0**	**11**	**29**
5.9 Nitrogen concentration in soil water rooting zone / N leaching flux	**1**	**0**	**1**	**0**	**2**	**0**	**0**	**1**	**0**	**0**	**0**	**2**	**7**	**18**
5.10 N content of plant tissue, e.g. in a common moss species. Preferably expressed relative to typical concentration for that species, i.e. as Moss Enrichment Index	**1**	**0**	**0**	**0**	**2**	**0**	**0**	**1**	**0**	**0**	**0**	**1**	**5**	**13**
5.11 Soil mineral N content (e.g. by extraction with 1M KCl)	**1**	**0**	**0**	**0**	**1**	**0**	**0**	**1**	**0**	**0**	**0**	**1**	**4**	**10**
5.12 Plant-available N, measured as mineralisable N	**1**	**0**	**0**	**0**	**1**	**0**	**0**	**1**	**0**	**0**	**0**	**1**	**4**	**10**
5.13 Plant-available N, measured using strong ion-exchange resins placed in the soil	**1**	**0**	**0**	**0**	**1**	**0**	**0**	**1**	**0**	**0**	**0**	**1**	**4**	**10**
5.14 Litter layer total C / N ratio	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**1**	**0**	**0**	**0**	**2**	**4**	**9**
5.15 Other nitrogen storage forms within plant tissue (asparagine, arginine and glutamine, *etc.*)	**0**	**0**	**0**	**0**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**3**	**8**

2 Potential ecosystem benefit metrics

2.1 Emissions metrics

[Metric 1.1] Agricultural emission density around designated sites (concentric zones) – measure of local pressures

Scores: Clear 2; Open 1; Targets 0; Scenarios 2; Sensitive 2; Scales 2; Easy 2; International 2; Charismatic 0; Sites 1; Endpoint 0; Cross-cutting 0. Total 14. **Weighted total 34**.
Method: Local emissions within a buffer zone (e.g. 1 km) surrounding a designated site
Units: kt N ha^{-1} yr^{-1}

Agricultural emission densities are an estimate of local emissions within a concentric zone surrounding a designated site, in kg NH_3-N ha^{-1} yr^{-1}. The metric includes total emission density as well as individual sector contributions (separately for beef, dairy, pigs, poultry *etc.*) where at least five individual holdings contribute to each data point. Where data were derived from fewer than 5 holdings, sectors were aggregated to suppress sensitive information, thereby ensuring that all outputs are non-disclosive. High emission densities indicate high potential for local mitigation, which is expected to be a useful indicator of pressure from high local concentrations and dry deposition of NH_3 to a designated site from local sources. The sectoral split can be helpful for identifying key source types and associated mitigation measures for strategic approaches to protected sites. The metric does not directly enable quantification of *vegetation impacts,* but can be used in combination with Metric 1.4, National (UK) Emissions reductions (NH_3, NO_x), to characterise the level and types of threats from atmospheric N. The metric has been developed for protected areas, which have known boundaries (high resolution GIS data).There are many different products available for mapped habitat extent and location beyond protected site boundaries, such as the UKCEH Land Cover Map (LCM[1]) or Natural England's Living Maps[2], however the emission density approach has not been implemented for these.

[Metric 1.2] Local spatial emission reductions (e.g. within buffer zones surrounding designated sites)

Scores: Clear 2; Open 1; Targets 1; Scenarios 2; Sensitive 2; Scales 2; Easy 0; International 2; Charismatic 0; Sites 1; Endpoint 0; Cross-cutting 0. Total 13. **Weighted total 31**.
Method: Local emissions reductions within a buffer zone (e.g. 1 km) surrounding a designated site
Units: kt N yr^{-1}

Spatial targeting of emissions near sensitive habitats and sites is considered an effective strategy to reduce the effects of local hotspots in concentration and dry deposition. Quantifying local emission reduction is a prerequisite to enabling concentration/deposition modelling and assessment against thresholds such as critical loads or levels but does not directly enable quantification of *vegetation impacts*.

[Metric 1.3] Sectoral emissions reductions (e.g. NH_3 by livestock category)

Scores: Clear 2; Open 2; Targets 1; Scenarios 2; Sensitive 2; Scales 1; Easy 0; International 2; Charismatic 0; Sites 0; Endpoint 0; Cross-cutting 0. Total 12. **Weighted total 28**.
Method: NO_x and NH_3 emissions from individual source categories
Units: kt N yr^{-1}

[1] https://www.ceh.ac.uk/ukceh-land-cover-maps.
[2] https://spaceforsmartergovernment.uk/index.php?symphony-page=case-study/eo-dip-living-maps-for-biodiversity-and-natural-capital/.

Potentially more relevant for policy makers than UK or regional emissions, since the source of decreases in emissions is specified in greater detail.

[Metric 1.4] National (UK) Emissions reductions (NH_3, NO_x)

Scores: Clear 2; Open 2; Targets 1; Scenarios 2; Sensitive 2; Scales 1; Easy 0; International 2; Charismatic 0; Sites 0; Endpoint 0; Cross-cutting 0. Total 12. **Weighted total 28**.
Method: Sum of NH_3 emissions from individual source categories
Units: kt N yr^{-1}

Total national NO_x and NH_3 emission data for the most recent year is readily available from the National Atmospheric Emissions Inventory (https://naei.beis.gov.uk/) which can be used to compare with future emissions scenario estimates (e.g. for 2030) which determines the total N deposition. The statistic gives no indication of spatial variability and only contributes to one component of N deposition. Whilst the majority of N deposition in the UK originates from UK emissions, other components are long-range transport from European emission sources and international shipping. Relevant for meeting national targets such as those in the NECR.

[Metric 1.5] Total emissions for UK countries (NH_3, NO_x)

Scores: Clear 2; Open 2; Targets 1; Scenarios 2; Sensitive 2; Scales 1; Easy 0; International 2; Charismatic 0; Sites 0; Endpoint 0; Cross-cutting 0. Total 12. **Weighted total 28.**
Method: Sum of NO_x and NH_3 emissions from individual source categories for England, Scotland, Wales, Northern Ireland
Units: kt N yr^{-1}

Data availability and limitations as for UK emissions reductions. Long-range transport means that pollutants also cross regional boundaries (e.g. emissions from Wales can be deposited in England). Relevant for understanding country specific contributions (and interactions) for meeting national targets such as those in the NECR.

2.2 Metrics of exposure

[Metric 2.1] Annual deposition of total N

Scores: Clear 2; Open 2; Targets 2; Scenarios 2; Sensitive 2; Scales 2; Easy 2; International 2; Charismatic 0; Sites 2; Endpoint 0; Cross-cutting 0. Total 18. **Weighted total 44**.
Method: Modelled N deposition for a location and habitat type generated by the CBED model at up to a 1x1 km resolution. To reduce the effects of inter-annual variation, typically a three-year rolling average is used for reporting, for example in Rowe *et al.* (2019). Nitrogen deposition rate is affected by vegetation type, with woodland receiving considerably more than open semi-natural habitats with low-growing vegetation. Separate maps are available for vegetation-specific deposition to each of these two main habitat types (as far as N deposition is concerned).
Units: kg N ha^{-1} yr^{-1}

Modelled N deposition provides a strong indication of the potential for N impacts on an area. Evidence for species and ecosystem responses to annual N deposition, from both N addition experiments and surveys, is well established across many habitat types (e.g. Bobbink & Hettelingh 2011; Emmett *et al*. 2011; Phoenix *et al*. 2012; Stevens *et al*. 2011b). Policy initiatives such as the CLRTAP make extensive use of the Critical Load concept, which is expressed in terms of annual deposition, so this metric is important. Data at 5x5 km resolution are available via the Air Pollution information System (APIS.ac.uk). There are currently no plans to publish data at finer resolution.

This metric is closely related to the target in the UK Government's Clean Air Strategy (Defra 2019), for "reduction of damaging deposition of reactive forms of nitrogen by 17% over England's protected priority sensitive habitats by 2030". The operational definition of this target, in terms of which habitats and protected sites to include and how to account for overlaps, is being discussed by Defra and the SNCBs. We have taken a preliminary approach, considering total reactive-N deposition onto a selection[3] of the habitats that are mapped as sensitive to nutrient-N in the Trends Report (e.g. Rowe *et al.* 2019). Total N deposition does not take into account habitat-specific critical loads but is a readily understood indicator of overall pressure on sensitive ecosystems.

[Metric 2.2] Atmospheric concentration of NH_3

Scores: Clear 2; Open 2; Targets 1; Scenarios 2; Sensitive 2; Scales 2; Easy 2; International 2; Charismatic 0; Sites 2; Endpoint 0; Cross-cutting 0. Total 17. **Weighted total 41**.
Method: Modelled NH_3 concentration for a location and habitat type generated by the FRAME Model at a 5x5 km resolution. To reduce the effects of inter-annual variation, typically a three-year rolling average is used for reporting.
Units: $\mu g\ NH_3\ m^{-3}$

Modelled NH_3 concentration provides a strong metric for the potential for concentration-based N impacts to a site, particularly where sensitive vegetation such as lower plants is an important component of the community. The relevance of this metric is supported by Critical Loads legislation, publications from N addition experiments (e.g. Sheppard *et al.* 2011) and surveys of woodland ground flora around ammonia sources (e.g. Pitcairn *et al.* 1998). Concentrations are available from Air Pollution information System (APIS.ac.uk) at 5 km by 5 km resolution, and so may not reflect small-scale variation in deposition over small distances, especially close to a source. Effects may be chronic, but responses to high concentrations of NH_3 have been observed over short timescales of less than a year (Sheppard *et al.* 2011).

[Metric 2.3] Cumulative deposition of total N in preceding 5 years (vegetation specific)

Scores: Clear 2; Open 2; Targets 1; Scenarios 2; Sensitive 1; Scales 2; Easy 1; International 0; Charismatic 0; Sites 0; Endpoint 0; Cross-cutting 1. Total 12. **Weighted total 29**.
Method: Cumulative N deposition over the 5 years preceding the evaluation, obtained from CBED model outputs at 5x5 km resolution, specific for the habitat type.
Units: $kg\ N\ ha^{-1}$

Research has demonstrated that N accumulates in ecosystems over years to decades and therefore cumulative N deposition over a period prior to present may be a better metric for understanding responses to N. A 30-year moving window of deposition is suggested as most appropriate for soils-based ecosystems (Payne *et al.* 2019; Rowe *et al.* 2017), but some components of ecosystems that receive N input directly from the atmosphere rather than via soil (such as bryophytes and lichens growing on trees or rocks) may respond over shorter timescales of 1 to 5 years (Rowe *et al.* 2017). The 5-year window is more responsive than a 30-year window to changes in deposition rate.

[Metric 2.4] Cumulative deposition of total N in preceding 30 years (vegetation specific)

Scores: Clear 2; Open 2; Targets 0; Scenarios 2; Sensitive 0; Scales 2; Easy 1; International 0; Charismatic 0; Sites 0; Endpoint 0; Cross-cutting 1. Total 10. **Weighted total 23**.

[3] Calcareous grassland; Dwarf shrub heath (wet & dry); Montane; Bog; Beech woodland (unmanaged); Acidophilous oak woodland (unmanaged); Scots Pine woodland (unmanaged); Dune grassland; Saltmarsh. See Trends Report 2020 (Rowe *et al.* in prep.).

Method: Cumulative N deposition over the 30 years preceding the evaluation, obtained from CBED model outputs at 5x5 km resolution, specific for the habitat type.
Units: kg N ha^{-1}

Research has demonstrated that N accumulates in ecosystems over years to decades and therefore cumulative N deposition over a period prior to present may be a better metric for understanding responses to N. A 30-year moving window of deposition is suggested as most appropriate for soils-based ecosystems (Payne *et al.* 2019; Rowe *et al.* 2017).

[Metric 2.5] Annual deposition of NH_y (vegetation specific)

Scores: Clear 1; Open 1; Targets 0; Scenarios 2; Sensitive 2; Scales 1; Easy 1; International 0; Charismatic 0; Sites 1; Endpoint 0; Cross-cutting 0. Total 9. **Weighted total 21**.
Method: Modelled deposition of reduced N (NH_y) for a location and habitat type generated by the CBED Model at a 5x5 km resolution.
Units: kg N ha^{-1} yr^{-1}

Reduced N has been found to be particularly harmful (in comparison to oxidised N) in some experiments that applied different forms of N (e.g. Sheppard 2014 #2608; van den Berg 2008 #2851). A recent analysis of survey data suggested that some habitats are more affected by NH_y deposition, other habitats more by NO_x deposition (van den Berg *et al.* 2016). However, there is little consistent evidence for differential responses to these different forms of N. This may be in part because of the difficulty of separating the effect of NH_y from that of NO_x or of total N deposition, but there are also theoretical reasons for doubting the relevance of NH_y deposition as a distinct measure. Reduced and oxidised N have the same effect in terms of acidification (Reuss & Johnson 1996), and the form of N in soil is more strongly influenced by the soil type, in particular the degree of aeration, than by the ratio of oxidised to reduced N in atmospheric inputs (Stevens *et al.* 2011a). Considering components of deposition (e.g. NHy, NOx, dry, wet), rather than total deposition, may complicate the picture unnecessarily.

[Metric 2.6] Annual deposition of NOx (vegetation specific)

Scores: Clear 1; Open 1; Targets 0; Scenarios 2; Sensitive 2; Scales 1; Easy 1; International 0; Charismatic 0; Sites 1; Endpoint 0; Cross-cutting 0. Total 9. **Weighted total 21**.
Method: Modelled deposition of oxidised N (NO_x) for a location and habitat type generated by the CBED Model at a 5x5 km resolution.
Units: kg N ha^{-1} yr^{-1}

As for NH_y deposition, there is insufficient evidence for a distinct effect of NO_x deposition to justify including this as a separate metric from total N deposition.

[Metric 2.7] Annual wet deposition of N

Scores: Clear 1; Open 1; Targets 0; Scenarios 2; Sensitive 2; Scales 1; Easy 1; International 0; Charismatic 0; Sites 1; Endpoint 0; Cross-cutting 0. Total 9. **Weighted total 21**.
Method: Modelled total wet-deposited N for a location and habitat type generated by the CBED Model at a 5x5 km resolution.
Units: kg N ha^{-1} yr^{-1}

As for NH_y deposition, there is insufficient evidence for a distinct effect of wet N deposition to justify including this as a separate metric from total N deposition.

[Metric 2.8] Annual dry deposition of N

Scores: Clear 1; Open 1; Targets 2; Scenarios 2; Sensitive 2; Scales 2; Easy 1; International 2; Charismatic 0; Sites 2; Endpoint 0; Cross-cutting 0. Total 36.

Method: Modelled total dry-deposited N for a location and habitat type generated by the CBED Model at a 5x5 km resolution.
Units: kg N ha^{-1} yr^{-1}

As for NH_y deposition, there is insufficient evidence for a distinct effect of dry N deposition to justify including this as a separate metric from total N deposition.

2.3 Designated site metrics

[Metric 3.1] Nitrogen Decision Framework: National evidence (Factor 1 score)

Scores: Clear 1; Open 2; Targets 2; Scenarios 2; Sensitive 1; Scales 2; Easy 2; International 2; Charismatic 0; Sites 2; Endpoint 1; Cross-cutting 1. Total 18. **Weighted total 43**.
Method: Combines different sources of information available at national scale.
Units: Categorical score.

A decision framework was developed (Jones *et al.* 2016) to provide a means of attributing N deposition as a threat to, or cause of, unfavourable habitat condition on protected sites. The framework provides a practical methodology for assessing the impacts of N deposition on protected sites in an objective way, which was previously lacking. It is based on a sound conceptual approach and is both robust and flexible enough to cope with additional information. The use of the Nitrogen Decision Framework is currently being piloted by the UK's country nature conservation bodies (CNCBs). Some CNCBs have preferred to rely solely on field-based assessment whilst others have more readily adopted model-based indicators of risk for site condition.

The Nitrogen Decision Framework combines information on site sensitivity to N impacts, using two main sources of information: i) N deposition assessed in relation to the critical load for a habitat (Factor 1 score) and ii) site-based evidence of impact (Factor 2 score). The Factor 1 score takes into account uncertainty in the N deposition estimate as well as uncertainty around the empirical critical load for nutrient N (CL_{empN}) for the habitat, encompassing aspects such as robustness score given for the CL_{empN} value, and whether the value was derived for that habitat or extrapolated from a similar habitat. As a default, the N deposition estimate is based on national level modelled/extrapolated N deposition with an associated uncertainty. Site-specific modelling or site-based measurements of N deposition can also be used, reducing the uncertainty. For the purposes of this study, only the Factor 1 score was assessed, using a lower estimate of uncertainty (+/- 20%, because site-specific modelling was carried out, compared with +/- 50% uncertainty recommended for use with deposition estimates using national models). The assessment assumed no site-based evidence of damage was available (see next section).

[Metric 3.2] Nitrogen Decision Framework: Site-based evidence (Factor 2 score)

Scores: Clear 2; Open 1; Targets 2; Scenarios 0; Sensitive 1; Scales 1; Easy 1; International 1; Charismatic 1; Sites 2; Endpoint 2; Cross-cutting 1. Total 15. **Weighted total 40**.
Method: Combines different sources of information available at site-specific scale.
Units: Categorical score.

As above, part of a decision framework developed to provide a means of attributing N deposition as a threat to, or cause of, unfavourable habitat condition on protected sites (Jones *et al.* 2016). This metric received a slightly lower evaluation than the National-evidence score because it is less applicable within the current project, and less applicable at a range of scales. In some instances it may not be possible to generate Factor 2 scores, e.g. for sites which lack additional sources of information on likely N impacts (e.g. quadrat data, targeted studies on N impacts at the site) or for habitats where there are no suitable indicators in the CSM guidance. However, many of the metrics discussed in subsequent metrics here could be used as site-based evidence, allowing Factor 2 scores to be calculated.

2.4 Vegetation effects metrics

[Metric 4.1] Exceedance of critical level for ammonia

Scores: Clear 2; Open 2; Targets 1; Scenarios 2; Sensitive 2; Scales 2; Easy 1; International 1; Charismatic 0; Sites 2; Endpoint 0; Cross-cutting 1. Total 16. **Weighted total 38**.
Method: The area which exceeds the critical level (1 µg m^{-3} or 3 µg m^{-3}) for NH_3. The amount of exceedance can also be readily calculated for a site, and an area-weighting approach could be used to calculate average exceedance for a larger area, *cf.* the "Excess Nitrogen" metric below.
Units: hectares, or µg NH_3 m^{-3}

A clear and readily understood indicator of excess NH_3. This metric can be applied at a variety of scales (national, regional and designated site), and for a variety of habitats and target species (1 µg m^{-3} for lichens and bryophytes; 3 µg m^{-3} for all other vegetation). The area exceeded is underpinned by a binary metric (exceeded or not) and so is unlikely to change rapidly, especially for areas with very high exceedance.

[Metric 4.2] Excess Nitrogen

Scores: Clear 1; Open 2; Targets 1; Scenarios 2; Sensitive 2; Scales 2; Easy 1; International 2; Charismatic 0; Sites 1; Endpoint 0; Cross-cutting 1. Total 15. **Weighted total 3**5.
Method: Sum of (exceedance of CL_{empN} x habitat area per grid cell) for all grid cells in a region, divided by the total habitat area in the region. See Methods Report, Hall *et al.* (2015).
Units: kg N ha^{-1} yr^{-1}

Excess Nitrogen is a proposed new name for *Average Accumulated Exceedance*, which has sometimes caused confusion as a term since it is based on accumulation across an area such as a 1 x 1 km grid cell, not cumulative deposition over time. Excess Nitrogen is the average amount by which CL_{empN} is exceeded, weighted by the areas of each habitat in the grid cell. The metric gives a good indication of how much a given area is affected, since it represents the degree to which sensitive habitats are exposed to N above their critical load.

[Metric 4.3] Exceedance of critical load for nutrient-N: amount of exceedance

Scores: Clear 1; Open 2; Targets 1; Scenarios 2; Sensitive 2; Scales 1; Easy 1; International 2; Charismatic 0; Sites 2; Endpoint 0; Cross-cutting 1. Total 15. **Weighted total 34**.
Method: The amount by which deposition exceeds the empirical critical load for nutrient-N.
Units: kg N ha^{-1} yr^{-1}

A clear and readily understood indicator of N deposition above CL_{empN} for a specific habitat. Exceedance can only be calculated for a single habitat with one deposition rate e.g. within a single grid cell. Thus, this metric is more suitable for site-specific than for wider-scale assessments.

[Metric 4.4] Exceedance of critical load for acidity: amount of exceedance

Scores: Clear 1; Open 2; Targets 1; Scenarios 2; Sensitive 2; Scales 1; Easy 1; International 2; Charismatic 0; Sites 2; Endpoint 0; Cross-cutting 1. Total 15. **Weighted total 34**.
Method: The amount by which deposition exceeds the critical load for acidity.
Units: keq ha^{-1} yr^{-1}

A clear and readily understood indicator of excess acidity (N and sulphur (S) deposition). As for nitrogen, exceedance can only be calculated for a specific habitat with a single deposition rate e.g. within a single grid cell. Thus, this metric is more suitable for site-specific than for wider-scale assessments.

[Metric 4.5] Area of sensitive habitat where CL_{empN} is exceeded

Scores: Clear 2; Open 2; Targets 1; Scenarios 2; Sensitive 2; Scales 1; Easy 1; International 2; Charismatic 0; Sites 0; Endpoint 0; Cross-cutting 1. Total 14. **Weighted total 33**.
Method: Total area of nutrient-N sensitive habitat for which the empirical critical load for nutrient-N is exceeded.
Units: km^2

This metric gives a good indication of the extent of potential damage to ecosystems within an area. It is more suitable for country-scale or regional assessment than for site assessments. It is widely reported e.g. in the annual Trends Report produced by the National Focal Centre (e.g. Rowe *et al.* 2020) and in Coordination Centre for Effects (CCE) status reports. The area exceeded is commonly reported in the media since it is readily understood. The area exceeded is underpinned by a binary metric (exceeded or not) and so is unlikely to change rapidly, especially for areas with very high exceedance.

[Metric 4.6] Area of protected sites (reported separately for SACs, SPAs and SSSIs/ASSIs) where CL_{empN} is exceeded for at least one sensitive feature

Scores: Clear 1; Open 2; Targets 1; Scenarios 2; Sensitive 2; Scales 1; Easy 1; International 0; Charismatic 0; Sites 2; Endpoint 0; Cross-cutting 1. Total 13. **Weighted total 30**.
Method: Total area of protected sites where CL_{empN} is exceeded for at least one sensitive feature.
Units: km^2

This metric is currently reported annually in the NFC Trends Report. It is an important statistic for legislative requirements. Calculating a combined area within all protected sites might make a better headline metric, although this would require overlaps between sites to be resolved among the different types of protected site.

2.5 Ecosystem condition metrics

Vegetation condition

Most indicators in this section are derived from observed species composition. A full species list of vascular plants, and preferably also bryophytes and lichens, is a rich resource of information. Observations from permanently located quadrats are particularly valuable, providing objective data of change over time. Estimates of species cover and frequency (occurrence within multiple quadrats) are also useful.

[Metric 5.1] Number of positive indicator species present

Scores: Clear 2; Open 2; Targets 1; Scenarios 0; Sensitive 2; Scales 2; Easy 2; International 1; Charismatic 0; Sites 2; Endpoint 2; Cross-cutting 0. Total 16. **Weighted total 43**.
Method: Survey of sites to check for presence of a list of indicator species.
Units: Number of selected indicators species present

Indicator species, e.g. as listed in Common Standards Monitoring (CSM) guidance (JNCC 2004), provide a rapid method for interpreting changes in species composition Positive indicator species are more closely related to habitat targets than is the full set of species, which may include invasive species, or those more typical of other habitats. The number of positive indicator species in a set of examples of habitats was found to be the measure that best correlated with SNCB habitat specialists' assessments of "overall habitat quality" (Rowe *et al.* 2016). Previous work has indicated that current CSM indicator species are not necessarily the most sensitive to N deposition (Stevens *et al.* 2009). Lists of N-sensitive indicator species could be compiled, although such a list might be less suitable for assessing changes to "overall habitat quality" in response to multiple drivers. Climate change is likely to change the typical species that occur in habitats, and decisions need to be made as to whether the list of species viewed as positive indicators would need to be adapted.

[Metric 5.2] Species richness

Scores: Clear 2; Open 1; Targets 1; Scenarios 0; Sensitive 2; Scales 2; Easy 1; International 1; Charismatic 0; Sites 2; Endpoint 2; Cross-cutting 2. Total 17. **Weighted total 42**.
Method: Survey of vascular plants and bryophytes within standard sized quadrats to determine how many species are present.
Units: Number of species

Negative impacts of nitrogen deposition on species richness have been observed in a wide range of habitats from both experimental N additions and experiments (Field *et al.* 2014; Maskell *et al.* 2010; Mountford *et al.* 1996). Whilst there is a good evidence base for this metric, it does require a good level of expertise to assess and putting single sites into context can be difficult. Species-richness data is not available (or is not collated) for all sites. Regression models that predict species-richness as a function of deposition could be used to infer changes in species-richness with deposition change (Hettelingh *et al.* 2013), although this approach does not take into account chemical and biological delays in responses to decreased pollution.

[Metric 5.3] Grass:forb ratio (& variants e.g. forb cover / total cover)

Scores: Clear 2; Open 1; Targets 1; Scenarios 0; Sensitive 2; Scales 2; Easy 2; International 1; Charismatic 0; Sites 2; Endpoint 2; Cross-cutting 0. Total 15. **Weighted total 41**.
Method: Survey of vascular plants within standard sized quadrats to determine percentage cover of grasses and forbs.
Units: e.g. ratio, proportion

Stevens *et al*. (2004) investigated the potential of grass / forb ratio as an indicator of N deposition and grass / forb ratio (or an alternative graminoid / forb ratio) is relatively easy to assess as they do not require species to be identified. This indicator may be better expressed as the ratio of forb / total cover, which is more mathematically robust (since it cannot be infinite) and increases with greater forb cover (Rowe *et al.* 2016). Whilst these seem to be good indicators, care should be taken in the use of such ratios because ratios will change in different seasons due to differing phenologies of the species.

[Metric 5.4] Mean habitat suitability for positive indicator species, modelled using MultiMOVE

Scores: Clear 1; Open 1; Targets 2; Scenarios 0; Sensitive 2; Scales 2; Easy 0; International 2; Charismatic 1; Sites 2; Endpoint 1; Cross-cutting 1. Total 15. **Weighted total 39**.
Method: Calculate the habitat suitability using MultiMOVE, either from site measurements of soil and/or floristics, or from modelled projections of soil / vegetation conditions.
Units: Proportion of maximum suitability (0-1)

As noted above, the number of positive indicator species present has been shown to reflect experts' assessments of overall habitat quality (Rowe *et al.* 2016). MultiMOVE is a set of regression models that predict the suitability of a site for individual species, based on environmental conditions such as vegetation height and annual rainfall. The mean simulated "habitat suitability" for positive indicator species has been adopted as a common metric for responses to the Working Group on Effects of the CLRTAP (Posch *et al.* 2014). Although this is not the easiest metric to explain, it is a robust indicator of overall habitat quality and so can be seen as an endpoint indicator for biodiversity.

[Metric 5.5] Species-based metrics of eutrophication, e.g. nitrophobe/nitrophile indices

Scores: Clear 2; Open 1; Targets 1; Scenarios 0; Sensitive 2; Scales 2; Easy 1; International 1; Charismatic 0; Sites 2; Endpoint 0; Cross-cutting 0. Total 12. **Weighted total 32**.
Method: Various depending on the metric used but likely to involve some kind of species survey.
Units: Various

Several metrics of eutrophication based on species composition have been developed and they are generally easy to apply. One of the best examples is a lichen-based one which divides species in to nitrophobes and nitrophiles (Wolseley *et al.* 2009) and has been used extensively as part of the Open Air Laboratories, OPAL, Lichen App project (Seed *et al.* 2013).

[Metric 5.6] Mean ‘Ellenberg N’ (eutrophication) score for present species

Scores: Clear 1; Open 1; Targets 1; Scenarios 0; Sensitive 2; Scales 2; Easy 1; International 1; Charismatic 0; Sites 2; Endpoint 0; Cross-cutting 0. Total 11. **Weighted total 29**.
Method: Survey of vascular plants within standard sized quadrats to determine species are present followed by averaging of scores for individual species. Scores can be weighted or unweighted by cover and can follow original European scores (Ellenberg *et al.* 1991) or those re-calculated for the UK (Hill *et al.* 2000; Hill *et al.* 2005).
Units: Ellenberg score

Ellenberg N values provide an estimate of a species’ preference for nutrient-rich habitats, on a scale of 1 (nutrient poor) to 9 (nutrient rich). For some habitats there is a very clear relationship between Ellenberg N and N deposition (e.g. Falkengren-Grerup *et al.* 1996) but for acid grasslands this was not found to be the case (Stevens *et al.* 2010).

[Metric 5.7] Ellenberg R

Scores: Clear 1; Open 1; Targets 1; Scenarios 0; Sensitive 2; Scales 2; Easy 1; International 1; Charismatic 0; Sites 2; Endpoint 0; Cross-cutting 0. Total 11. **Weighted total 29**.
Method: Survey of vascular plants within standard sized quadrats to determine species are present followed by averaging of scores for individual species. Scores can be weighted or unweighted by cover and can follow original European scores (Ellenberg *et al.* 1991) or those re-calculated for the UK (Hill *et al.* 2000; Hill *et al.* 2005).
Units: Ellenberg score

Similar to Ellenberg N, Ellenberg R (Reaction) values provide an estimate of a species preference for acid or basic soils. The scale runs from 1 for acid to 9 for basic soils. Many studies, particularly those in poorly buffered soils, have found relationships between Ellenberg R and N inputs (e.g. Stevens *et al.* 2010). However, it is not possible to separate effects of N deposition from other acidifying pollutants.

[Metric 5.8] Cover-weighted mean typical height for present species

Scores: Clear 2; Open 1; Targets 1; Scenarios 0; Sensitive 2; Scales 0; Easy 1; International 1; Charismatic 1; Sites 2; Endpoint 0; Cross-cutting 0. Total 11. **Weighted total 29**.
Method: Survey of vascular plants within standard sized quadrats followed by looking up species typical height in a database and calculating a weighted average based on percent cover.
Units: Mean height (mm)

Since more competitive plants are typically taller, areas impacted by eutrophication are likely to be dominated by species which are taller. By using typical height rather than actual height the effects of management on height are removed. This measure does require a reasonable level of botanical expertise since all species need to be identified, cover estimated, and typical heights determined.

Biogeochemical condition

[Metric 5.9] Nitrogen concentration in soil water rooting zone / N leaching flux

Scores: Clear 1; Open 0; Targets 1; Scenarios 0; Sensitive 2; Scales 0; Easy 0; International 1; Charismatic 0; Sites 0; Endpoint 0; Cross-cutting 2. Total 7. **Weighted total 18**.
Method: Analysis of soil water obtained using suction samplers (e.g. Rhizons) or lysimeters.
Units: mg N L^{-1} (for concentration) or kg N ha^{-1} yr^{-1} (for flux)

Non-zero values of N in soil water are a good indicator of advanced N saturation, although it should be noted that damaging effects of N may happen (via increased plant uptake of N) before any N appears in the soil solution, so zero values do not mean there has been no damage. The concentration of N in leachate is relevant for the EU limit for drinking water, which is set at 50 mg of nitrate per litre. This is a useful indicator, but its measurement requires training and laboratory facilities.

[Metric 5.10] N content of plant tissues

Scores: Clear 1; Open 0; Targets 0; Scenarios 0; Sensitive 2; Scales 0; Easy 0; International 1; Charismatic 0; Sites 0; Endpoint 0; Cross-cutting 1. Total 5. **Weighted total 13**.
Method: Collection of above-ground plant tissues from site and analysis of total N using an analyser or digest.
Units: mg N g^{-1} dry plant tissue

Tissue N content is a very responsive plant trait which changes rapidly in response to changing N levels (Dise *et al.* 1998) and many studies have reported that plant tissue N increases with N addition (Phoenix *et al.* 2012) meaning this may be a good metric to assess change. However, not all gradient studies have identified relationships, indicating that not all species are suitable for use (Stevens *et al.* 2006).

[Metric 5.11] Soil mineral N content (e.g. by extraction with 1M KCl)

Scores: Clear 1; Open 0; Targets 0; Scenarios 0; Sensitive 1; Scales 0; Easy 0; International 1; Charismatic 0; Sites 0; Endpoint 0; Cross-cutting 1. Total 4. **Weighted total 10**.
Method: Collection of soil samples with KCl extraction followed by analysis of fresh soils for nitrate and ammonium content using an auto-analyser or ion chromatograph.
Units: mg N kg^{-1} soil

Soil mineral nitrogen content would typically be expected to increase as the available nitrogen increases and in experiments has often been found to do so. However, mineral N can vary depending on weather conditions and time of year. As with N concentration in soil water (see above), damaging effects of N may happen before any N appears in the soil solution, so zero values do not mean there has been no damage. In a regional survey, soil mineral N was not found to be related to N inputs (Stevens *et al.* 2006). However, in the Countryside Survey, mineral N was found to be a reasonably effective predictor of site productivity as indicated by mean Ellenberg N score (Rowe *et al.* 2011). Mineralisable N (see below) was slightly better but is more expensive to measure.

[Metric 5.12] Plant-available N, measured as mineralisable N

Scores: Clear 1; Open 0; Targets 0; Scenarios 0; Sensitive 1; Scales 0; Easy 0; International 1; Charismatic 0; Sites 0; Endpoint 0; Cross-cutting 1. Total 4. **Weighted total 10**.
Method: analysis of the change in soil mineral N content (by KCl extraction) after an incubation period e.g. 14 days.
Units: mg N kg^{-1} soil

Mineralizable N content was found to be correlated with N deposition in the Countryside Survey, (Rowe *et al.* 2012), and was the best co-predictor (with soil C content) of site productivity as indicated by mean Ellenberg N score (Rowe *et al.* 2011). Mineralizable N is a more sensitive indicator at relatively low levels of N pollution than is soil-solution N or KCl-extractable N, since some N is likely to be released into solution during laboratory incubation unless N is very unavailable. Whilst this has the potential to be a good indicator it takes some time to collect data due to the need for an incubation and it requires laboratory analysis. Mineralisation rates vary seasonally.

[Metric 5.13] Plant-available N, measured using strong ion-exchange resins placed in the soil

Scores: Clear 1; Open 0; Targets 0; Scenarios 0; Sensitive 1; Scales 0; Easy 0; International 1; Charismatic 0; Sites 0; Endpoint 0; Cross-cutting 1. Total 4. **Weighted total 10**.
Method: Ion exchange resins are placed into the soil. These bind available N mimicking plant uptake. After being in the field for a standard length of time (days to months depending on the resin and N levels in the soils) ions are extracted using acids and analysed for mineral N content.
Units: mg N L^{-1} per unit of time

Ion exchange resins have been related to N inputs in a number of studies and like mineralisation offer an integrated measure of soil N over time. This method requires field incubation and laboratory analysis but there are commercially available services. Plant-available N varies seasonally.

[Metric 5.14] Litter layer total C / N ratio

Scores: Clear 0; Open 0; Targets 0; Scenarios 0; Sensitive 1; Scales 0; Easy 0; International 1; Charismatic 0; Sites 0; Endpoint 0; Cross-cutting 2. Total 4. **Weighted total 9**.
Method: Analysis of C and N content in litter samples
Units: g C g^{-1} N

Soil C/N values change only slowly, because of large N and C stocks in soil, and may not change in a consistent direction with N pollution (Rowe *et al.* 2017). By contrast, litter C/N ratio is more responsive to N pollution, since it reflects the effort plants put into recycling N from their leaves before senescence. Litter C/N has an important influence over N cycling. It is relatively easily assessed although litter collection is easier in some habitats than others. It requires multiple samples and laboratory analysis. Due to decomposition processes litter C/N varies through the year.

[Metric 5.15] Other nitrogen storage forms within plant tissue (asparagine, arginine and glutamine, *etc.*)

Scores: Clear 0; Open 0; Targets 0; Scenarios 0; Sensitive 2; Scales 0; Easy 0; International 0; Charismatic 0; Sites 0; Endpoint 0; Cross-cutting 1. Total 3. **Weighted total 8**.
Method: Depends on the N form but for amino acids is likely to be HPLC
Units: Dependent on form and analysis used

The measurement of forms of N used within plants has good potential as a sensitive metric, but the evidence base for some forms, and in some plant types, is more established than others. This method requires specialist laboratory analysis.

3 Conclusions

Metrics that were considered for illustrating the results of the different pollution scenarios explored in the current project are shown in Table 4. Metrics considered potentially useful but for which data within the current project were not available are listed in Table 5, and could be explored in future work. Metrics that were reviewed but eliminated as not meeting one or more essential criteria are listed in Table 6, along with the reason(s) for their exclusion.

Table 4. Metrics included as illustrations of different pollution scenarios. Metrics are listed firstly in order of the group (type of metric) and then by overall score.

Metric	Weighted score
1.1 Agricultural emission density around designated sites (concentric zones) – measure of local pressure	34
1.2 Local spatial emission reductions (e.g. within buffer zones surrounding designated sites)	31
1.3 Sectoral emissions reductions (e.g. NH_3 by livestock category)	28
1.4 National (UK) Emissions reductions (NH_3, NO_x)	28
1.5 Regional emissions (NH_3, NO_x) – Devolved Administration level (E, W, Sc, NI)	28
2.1 Annual deposition of total N (vegetation specific)	44
2.2 Atmospheric concentration of NH_3	41
4.1 Exceedance of critical level for ammonia: amount of exceedance	38
4.2 Excess Nitrogen	35
4.3 Exceedance of critical load for nutrient-N: amount of exceedance	34
4.4 Exceedance of critical load for acidity: amount of exceedance	34
4.5 Area of sensitive habitat where CL_{empN} is exceeded (% of total sensitive-habitat area)	33
4.6 Area of protected sites (reported separately for SACs, SPAs and SSSIs/ASSIs) where CL_{empN} is exceeded for at least one sensitive feature	30

Table 5. Potentially useful metrics that were not calculated within the current project.

Metric	Weighted score
2.3 Cumulative deposition of total N in preceding 5 years (vegetation specific)	29
2.4 Cumulative deposition of total N in preceding 30 years (vegetation specific)	23
2.5 annual deposition of NH_y (vegetation specific)	21
2.6 annual deposition of NO_x (vegetation specific)	21
2.7 annual wet deposition of N	21
2.8 annual dry deposition of N	21
3.1 Nitrogen Decision Framework: National evidence (Factor 1 score)	43
3.2 Nitrogen Decision Framework: Site-based evidence (Factor 2 score)	40
5.1 Number of positive indicator species present, e.g. common standards monitoring indicator species	43
5.2 Species richness (including breakdown to vascular species and lower plants)	42
5.3 Grass:forb ratio (& variants, e.g. forb cover / total cover)	41
5.4 Mean habitat suitability for positive indicator species modelled using MultiMOVE	39
5.5 Species-based metrics of eutrophication, e.g. nitrophobe/nitrophile indices	32
5.6 Mean 'Ellenberg N' (eutrophication) score for present species	29
5.7 Mean 'Ellenberg R' (acidity) score for present species	29
5.8 Cover-weighted mean typical height for present species	29
5.9 Nitrogen concentration in soil water rooting zone / N leaching flux	18
5.10 N content of plant tissue, e.g. in a common moss species. Preferably expressed relative to typical concentration for that species, i.e. as Moss Enrichment Index (Rowe *et al.* 2017).	13
5.11 Soil mineral N content (e.g. by extraction with 1M KCl)	10
5.12 Plant-available N, measured as mineralisable N.	10
5.13 Plant-available N, measured using strong ion-exchange resins placed in the soil	10
5.14 Litter layer total C / N ratio	9
5.15 Other nitrogen storage forms within plant tissue (asparagine, arginine and glutamine, *etc.*)	8

Table 6. Metrics that were considered unsuitable for use in assessing benefits of decreases in N pollution, showing which essential criteria they did not meet.

Metric	Concrete	Robust / reasonably certain	Enables assessment	Sufficiently sensitive
Cumulative deposition of total N since 1990 (vegetation specific)	Yes	Yes	No	No
Exceedance of critical load for nutrient-N: binary (exceeded or not)	Yes	Yes	Yes	No
Exceedance of critical load for acidity: binary (exceeded or not)	Yes	Yes	Yes	No
Measured vegetation height	Yes	Yes	No	Yes
Soil (0-15 cm, below litter) total C / N ratio	Yes	Yes	Yes	No
Atmospheric concentration of NO_x	Yes	No	No	No
Critical load for nutrient-N	Yes	Yes	No	No
Critical load for acidity	Yes	Yes	No	No

4 References

Bobbink, R. & Hettelingh, J.P. (2011) Review and revision of empirical critical loads and dose-response relationships: Proceedings of an expert workshop, Noordwijkerhout, 23-25 June 2010. Coordination Centre for Effects, RIVM, NL.

Defra. (2019) Clean Air Strategy 2019. https://www.gov.uk/government/publications/clean-air-strategy-2019. .

Dise, N.B., Matzner, E. & Gundersen, P. (1998) Synthesis of nitrogen pools and fluxes from European forest ecosystems. Water Air and Soil Pollution 105, 143-154.

Ellenberg, H., Weber, H.E., Dull, R., Wirth, V., Werner, W. & Paulissen, D. (1991) Zeigerwerte von pflanzen in mitteleuropa. Scripta Geobotanica 2, 248.

Emmett, B.A., Rowe, E.C., Stevens, C.J., Gowing, D.J., Henrys, P.A., Maskell, L.C. & Smart, S.M. (2011) Interpretation of evidence of nitrogen impacts on vegetation in relation to UK biodiversity objectives. JNCC Report 449. JNCC, Peterborough, UK., p. 105.

Field, C.D., Dise, N.B., Payne, R.J., Britton, A.J., Emmett, B.A., Helliwell, R.C., Hughes, S., Jones, L., Lees, S., Leake, J.R., Leith, I.D., Phoenix, G.K., Power, S.A., Sheppard, L.J., Southon, G.E., Stevens, C.J. & Caporn, S.J.M. (2014) The role of nitrogen deposition in widespread plant community change across semi-natural habitats. Ecosystems 17, 864-877.

Hall, J., Curtis, C., Dore, T. & Smith, R. (2015) Methods for the calculation of critical loads and their exceedances in the UK. http://www.cldm.ceh.ac.uk/publications/uk-status-reports#overlay-context=uk. CEH. Report to Defra under contract AQ0826.

Hettelingh, J.-P., Posch, M. & Stevens, C. (2013) Regionalization of dose-response relationships established from gradient studies., Presentation at 23rd CCE Workshop, 8-11th April 2013, Copenhagen. http://wge-cce.org/Activities/Workshops/Past_workshops/Denmark_2013

Hill, M.O., Roy, D.B., Mountford, J.O. & Bunce, R.G.H. (2000) Extending Ellenberg's indicator values to a new area: an algorithmic approach. Journal of Applied Ecology 37, 3-15.

Hill, M.O., Roy, D.B. & Preston, C. (2005) Development of environmental indices (Ellenberg-style scores) for British bryophytes., in: Smart, S., Evans, C.D., Rowe, E.C., Wamelink, G.W.W., Wright, S., Scott, A., Roy, D., Preston, C., Hill, M., Rothery, P., Bullock, J., Moy, I., Emmett, B.A. & Maskell, L. (Eds.), Atmospheric nitrogen pollution impacts on biodiversity: Phase 1 - Model development and testing (Appendices). Centre for Ecology and Hydrology, Lancaster, UK., pp. 116-123.

JNCC. (2004) Common Standards Monitoring: Introduction to the guidance manual.

Jones, L., Hall, J., Strachan, I., Field, F., Rowe, E., Stevens, C., Caporn, S., Mitchell, R., Britton, A., Smith, R., Bealey, B., Masante, D., Hewison, R., Hicks, K., Whitfield, C. & Mountford, E. (2016) A decision framework to attribute atmospheric nitrogen deposition as a threat to or cause of unfavourable habitat condition on protected sites. JNCC Report 579. JNCC, Peterborough, UK., p. 20.

Maskell, L.C., Smart, S.M., Bullock, J.M., Thompson, K. & Stevens, C.J. (2010) Nitrogen deposition causes widespread loss of species richness in British habitats. Global Change Biology 16, 671-679.

Mountford, J.O., Lakhani, K.H. & Holland, R.J. (1996) Reversion of grassland vegetation following the cessation of fertilizer application. Journal of Vegetation Science 7, 219-228.

Payne, R.J., Campbell, C., Britton, A.J., Mitchell, R.J., Pakeman, R.J., Jones, L., Ross, L.C., Stevens, C.J., Field, C., Caporn, S.J.M., Carroll, J., Edmondson, J.L., Carnell, E.J., Tomlinson, S., Dore, A.J., Dise, N. & Dragosits, U. (2019) What is the most ecologically-meaningful metric of nitrogen deposition? Environmental Pollution 247, 319-331.

Phoenix, G.K., Emmett, B.A., Britton, A.J., Caporn, S.J.M., Dise, N.B., Helliwell, R., Jones, L., Leake, J.R., Leith, I.D., Sheppard, L.J., Sowerby, A., Pilkington, M.G., Rowe, E.C., Ashmore, M.R. & Power, S.A. (2012) Impacts of atmospheric nitrogen deposition: responses of multiple plant and soil parameters across contrasting ecosystems in long-term field experiments. Global Change Biology 18, 1197-1215.

Pitcairn, C.E.R., Leith, I.D., Sheppard, L.J., Sutton, M.A., Fowler, D., Munro, R.C., Tang, S. & Wilson, D. (1998) The relationship between nitrogen deposition, species composition and foliar nitrogen concentrations in woodland flora in the vicinity of livestock farms. Environmental Pollution 102, 41-48.

Posch, M., Hettelingh, J.-P., Slootweg, J. & Reinds, G.-J. (2014) Deriving critical loads based on plant diversity targets., in: Slootweg, J., Posch, M., Hettelingh, J.-P. & Mathijssen, L. (Eds.), Modelling and Mapping the impacts of atmospheric deposition on plant species diversity in Europe. CCE Status Report 2014., Coordination Centre for Effects, RIVM, Bilthoven, Netherlands., pp. 41-46.

Reuss, J.O. & Johnson, D.W. (1996) Acid deposition and the acidification of soils and waters. Ecological studies 59, Springer -Verlag New York Inc.

Rowe, E., Mitchell, Z., Tomlinson, S., Levy, P., Banin, L.F., Sawicka, K., Martín Hernandez, C. & Dore, D. (2020) Trends Report 2020: Trends in critical load and critical level exceedances in the UK. Report to Defra under Contract AQ0843. CEH Project: NEC05708., https://uk-air.defra.gov.uk/library/reports?report_id=1001.

Rowe, E., Sawicka, K., Mitchell, Z., Smith, R., Dore, D., Banin, L.F. & Levy, P. (2019) Trends Report 2019: Trends in critical load and critical level exceedances in the UK. Report to Defra under Contract AQ0843. CEH Project: NEC05708., p. 79.

Rowe, E.C., Emmett, B.A., Frogbrook, Z.L., Robinson, D.A. & Hughes, S. (2012) Nitrogen deposition and climate effects on soil nitrogen availability: Influences of habitat type and soil characteristics. Science of the Total Environment 434, 62-70.

Rowe, E.C., Emmett, B.A., Smart, S.M. & Frogbrook, Z.L. (2011) A new net mineralizable nitrogen assay improves predictions of floristic composition. Journal of Vegetation Science 22, 251-261.

Rowe, E.C., Ford, A.E.S., Smart, S.M., Henrys, P.A. & Ashmore, M.R. (2016) Using qualitative and quantitative methods to choose a habitat quality metric for air pollution policy evaluation. PLOS-ONE 11(8). doi:10.1371/journal.pone.0161085.

Rowe, E.C., Jones, L., Dise, N.B., Evans, C.D., Mills, G., Hall, J., Stevens, C.J., Mitchell, R.J., Field, C., Caporn, S.J., Helliwell, R.C., Britton, A.J., Sutton, M., Payne, R.J., Vieno, M., Dore, A.J. & Emmett, B.A. (2017) Metrics for evaluating the ecological benefits of decreased nitrogen deposition. Biological Conservation 212, 454-463.

Seed, L., Wolseley, P., Gosling, L., Davies, L. & Power, S.A. (2013) Modelling relationships between lichen bioindicators, air quality and climate on a national scale: Results from the UK OPAL air survey. Environmental Pollution 182, 437-447.

Sheppard, L.J., Leith, I.D., Mizunuma, T., Cape, J.N., Crossley, A., Leeson, S., Sutton, M.A., van Dijk, N. & Fowler, D. (2011) Dry deposition of ammonia gas drives species change faster than wet deposition of ammonium ions: evidence from a long-term field manipulation. Global Change Biology 17, 3589-3607.

Stevens, C.J., Caporn, S.J.M., Maskell, L.C., Smart, S.M., Dise, N.B. & Gowing, D.J. (2009) Detecting and attributing air pollution impacts during SSSI condition assessment. JNCC Report No. 426. JNCC, Peterborough. ISSN 0963-8091 .

Stevens, C.J., Dise, N.B., Gowing, D.J.G. & Mountford, J.O. (2006) Loss of forb diversity in relation to nitrogen deposition in the UK: regional trends and potential controls. Global Change Biology 12, 1823-1833.

Stevens, C.J., Dise, N.B., Mountford, J.O. & Gowing, D.J. (2004) Impact of nitrogen deposition on the species richness of grasslands. Science 303, 1876-1879.

Stevens, C.J., Manning, P., van den Berg, L.J.L., de Graaf, M.C.C., Wamelink, G.W.W., Boxman, A.W., Bleeker, A., Vergeer, P., Arroniz-Crespo, M., Limpens, J., Lamers, L.P.M., Bobbink, R. & Dorland, E. (2011a) Ecosystem responses to reduced and oxidised nitrogen inputs in European terrestrial habitats. Environmental Pollution 159, 665-676.

Stevens, C.J., Smart, S.M., Henrys, P.A., Maskell, L.C., Walker, K.J., Preston, C.D., Crowe, A., Rowe, E.C., Gowing, D.J. & Emmett, B.A. (2011b) Collation of evidence of nitrogen impacts on vegetation in relation to UK biodiversity objectives. JNCC Report 447. JNCC, Peterborough, ISSN 0963-8091.

van den Berg, L.J.L., Jones, L., Sheppard, L.J., Smart, S.M., Bobbink, R., Dise, N.B. & Ashmore, M.R. (2016) Evidence for differential effects of reduced and oxidised nitrogen deposition on vegetation independent of nitrogen load. Environmental Pollution 208, 890-897.

Wolseley, P.A., Leith, I.D., Van Dijk, N. & Sutton, M.A. (2009) Macrolichens on twigs and trunks as indicators of ammonia concentrations across the UK – a practical method., in:

Sutton, M.A., Reis, S. & Baker, S.M.H. (Eds.), Atmospheric Ammonia– detecting emission changes and environmental impacts. . Springer Science, pp. 101-108.